VEHICLE TECHNOLOGIES OFFICE

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Overview of the DOE VTO Electric Drive Technologies R&D Program

June 7, 2016

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Steven Boyd

Organizational Overview

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Vehicle Technologies Office

Hybrid Electric Systems

Energy Storage

Electric Drive Technologies (EDT) Program

Vehicle Systems

Industry

Federal Agencies

Academia

National Labs

EDT Major Challenges and Barriers

Cost remains the leading factor

Decrease motor cost that is predominately driven by total material and overall size of the motor

- Develop new magnets without heavy rare-earth.
- Develop electrical steels.
- Develop motor designs without rare-earth magnets that meet targets.
- Understand and improve thermal management.

Size and mass constrain the number of potential vehicle applications

- Focus on significant power density increase.

Need for higher power devices

- Driven by market demand.

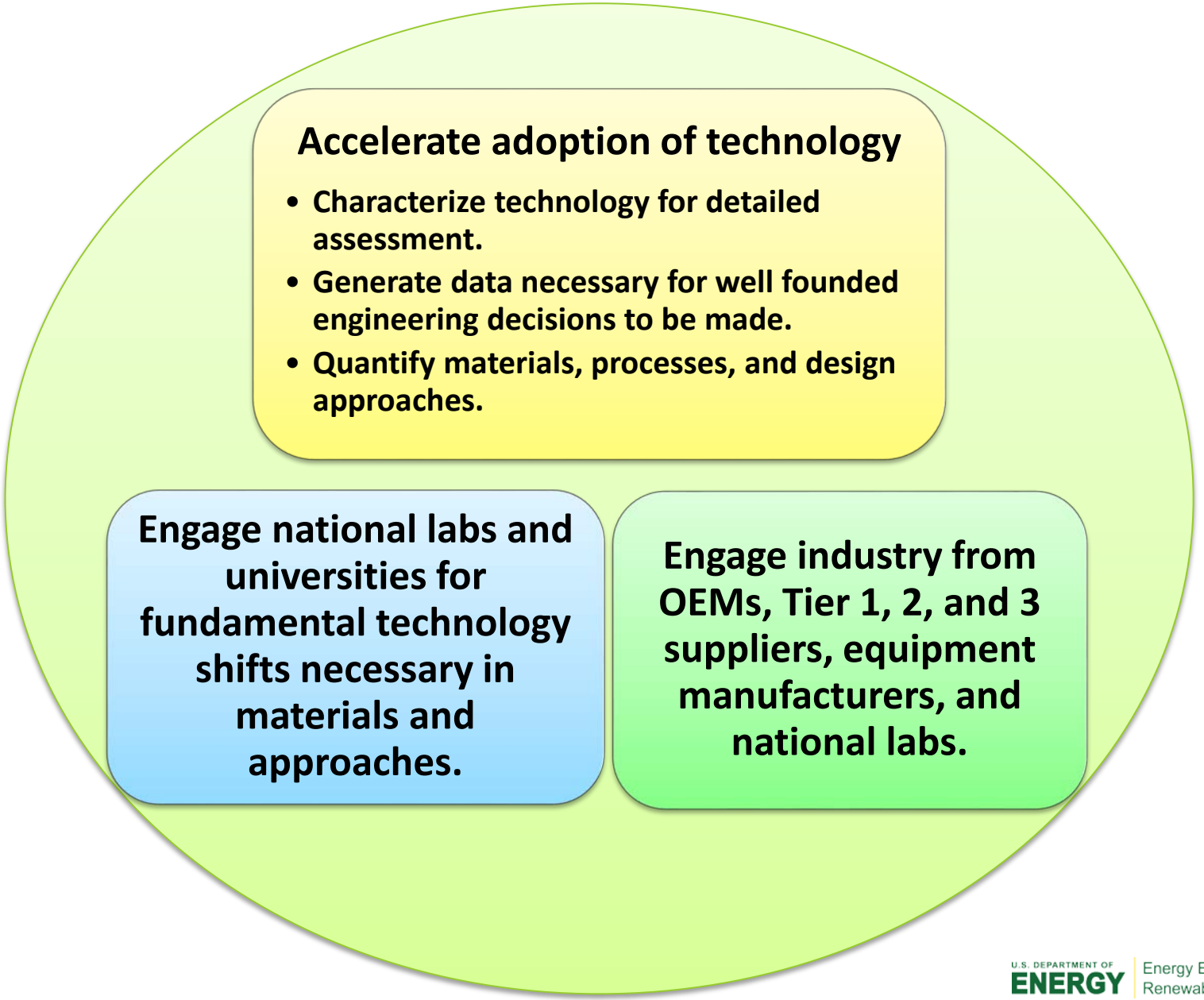
Motor efficiency

- Dependent on system needs and specific motor applications.

Taking advantage of WBG requires significant technology innovations beyond current silicon-based systems

- Packaging electrical performance and temperature capability.
- Thermal management and reliability.

EDT Strategy

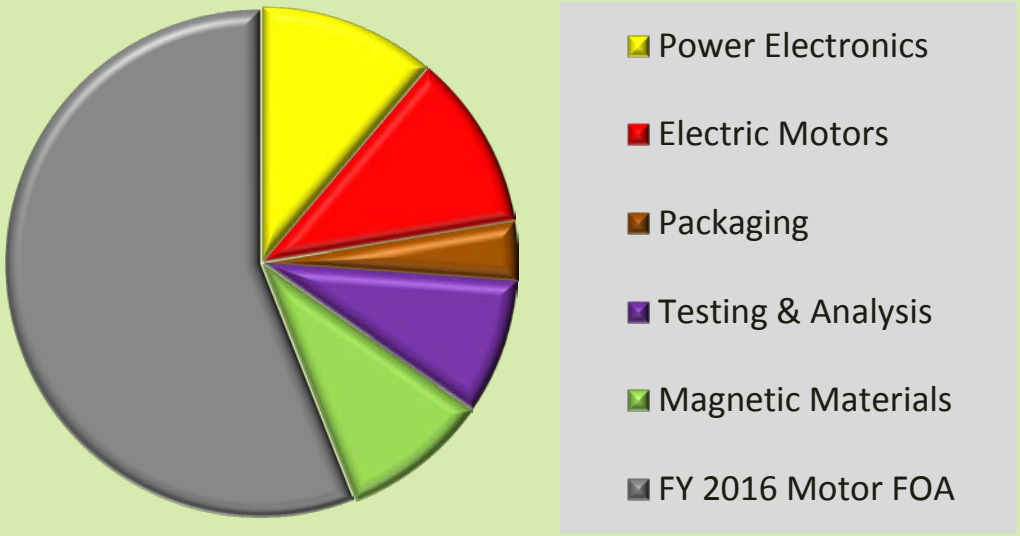


EDT Program Overview

Develop electric drive technologies and designs to:

- ❑ **Reduce cost;**
- ❑ **Improve performance; and**
- ❑ **Increase reliability.**

FY 2016 EDT Budget ($38M Enacted)



R&D accelerates:

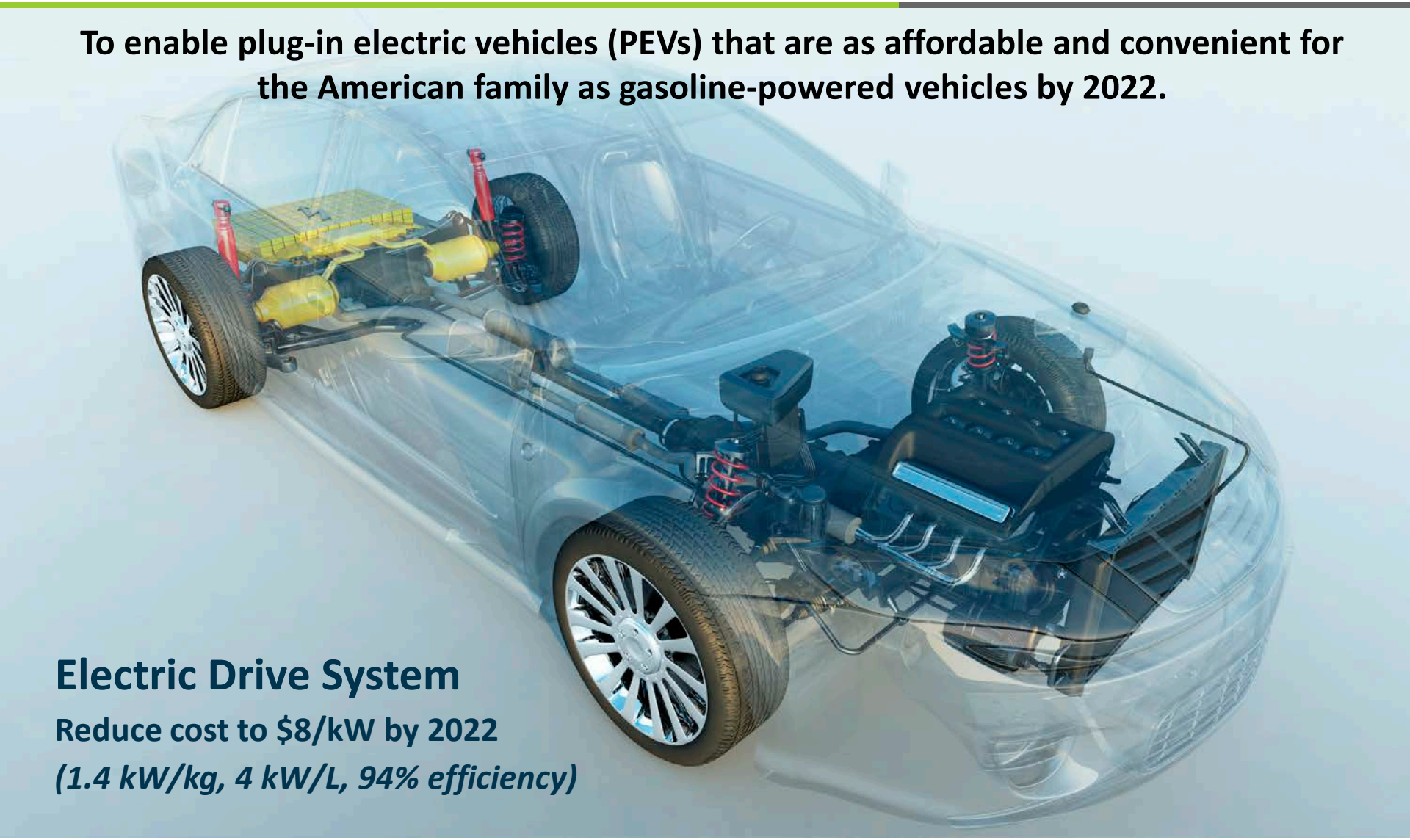
- ❑ Adoption of wide bandgap (WBG) semiconductors.
- ❑ Reduction or elimination of rare earth magnets.

FY16 Funding Opportunity Announcement (FOA) Topic:

- ❑ *Advances for the Production of Low Cost Electric Drive Vehicle Motors.*

EV Everywhere Grand Challenge

To enable plug-in electric vehicles (PEVs) that are as affordable and convenient for the American family as gasoline-powered vehicles by 2022.



Electric Drive System

Reduce cost to $8/kW by 2022

(1.4 kW/kg, 4 kW/L, 94% efficiency)

EDT – Focus Over Time

1995 to 2005

Basic automotive components

(125°C junction and 2 to 10 kHz operation)

- **Automotive Integrated Power Modules (AIPM).**
- **Automotive Electric Motor Drive (AEMD).**
- **Move from industrial based to automotive dynamic environment design.**

2005 to 2015

Integration, fundamental component and materials understandings/development

(150°C junction and up to 12 kHz operation)

- **High temperature operation (engine coolant loop capable)**
- **Integrated motor and power electronics (elimination of connectors, cabling, and housing).**
- **Elimination of redundant functionality.**
- **Manufacturing process (vertical & simplification).**
- **Understanding of the science of performance and failures.**

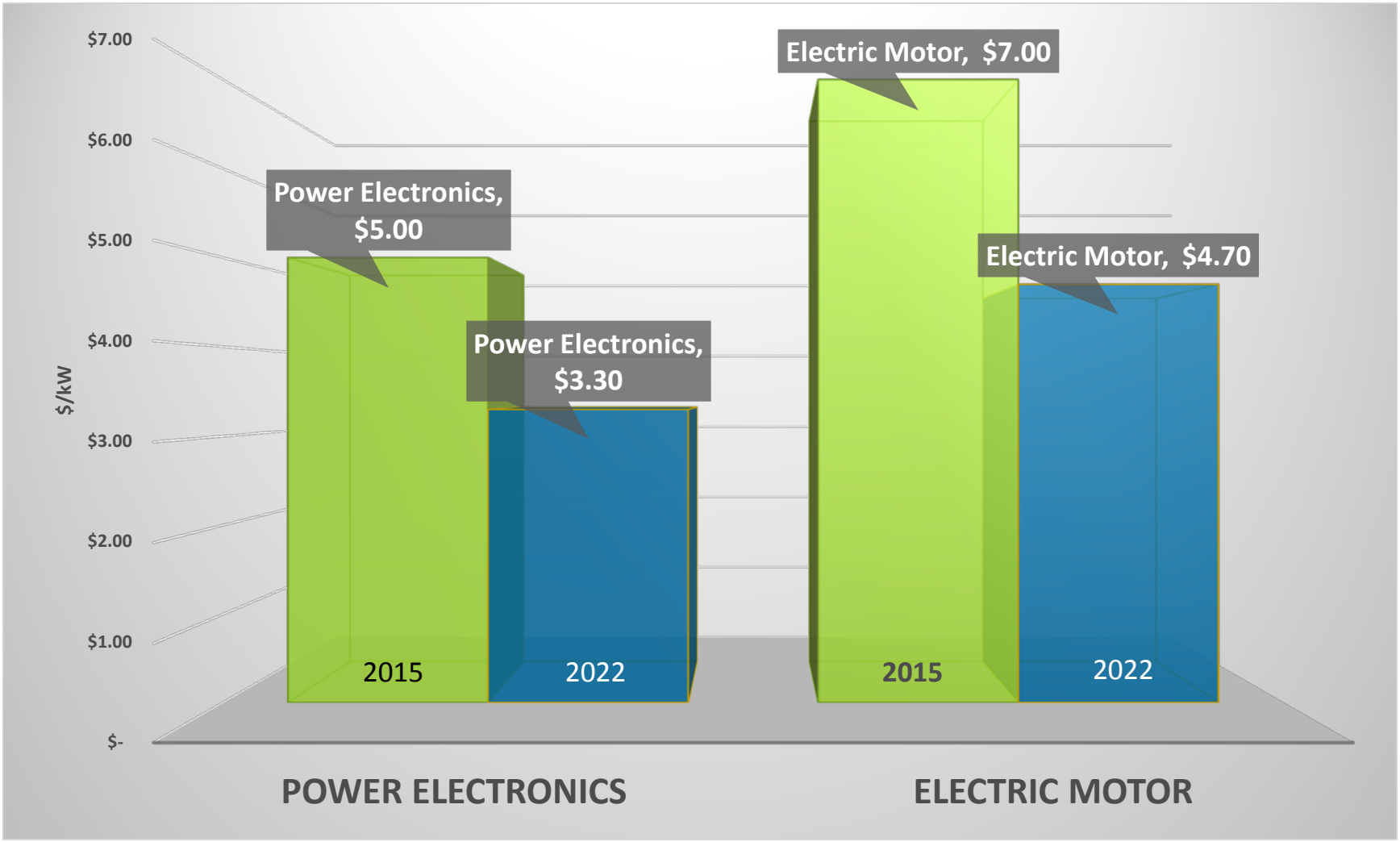
2015 to 2022

Advanced high density packaging and operating strategies with high frequency

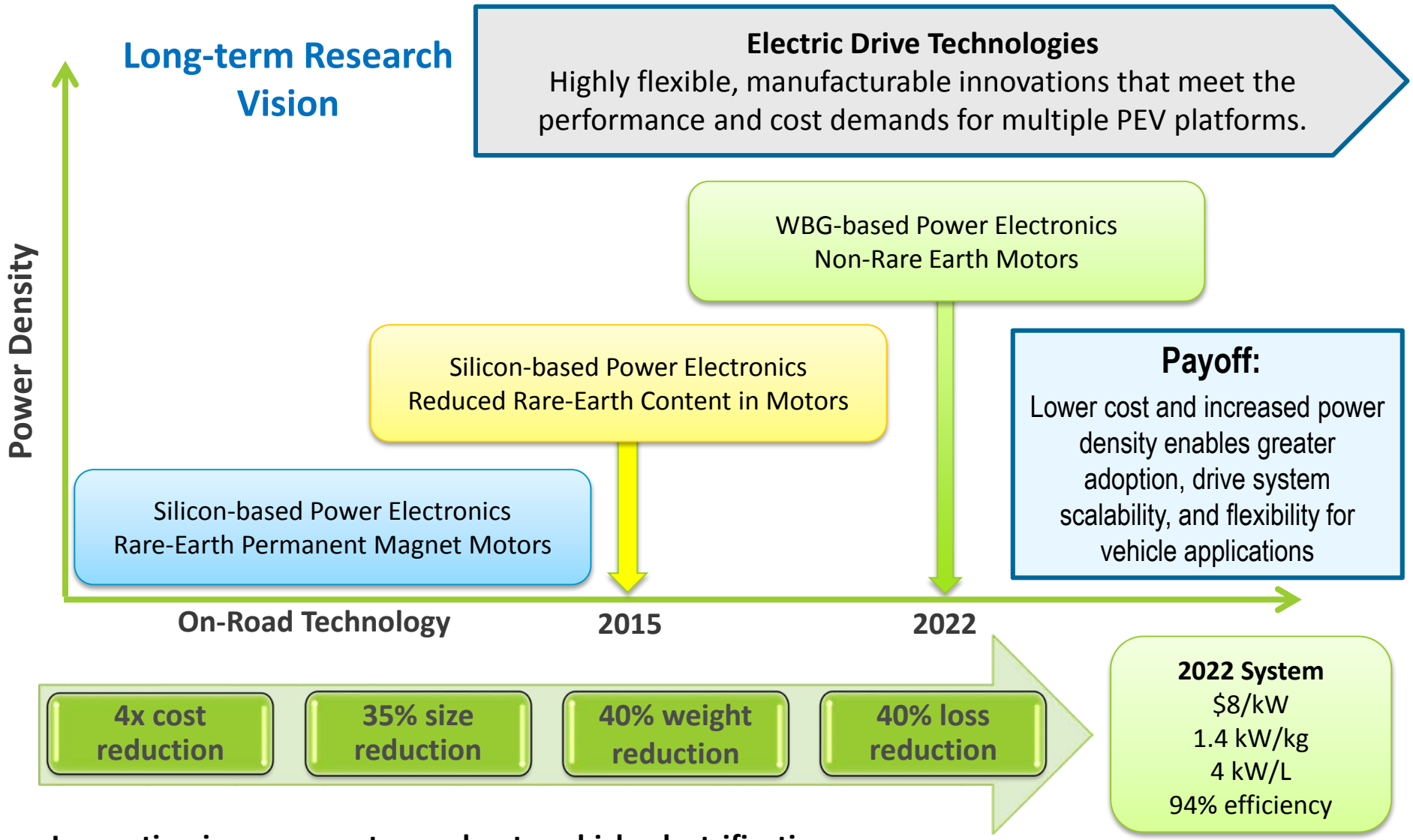
(250°C junction and up to 100 kHz operation)

- **3D Packaging and miniaturization.**
- **New materials and processes.**
- **Control strategies.**
- **High performance computing.**

EDT - Cost Targets



EDT Roadmap

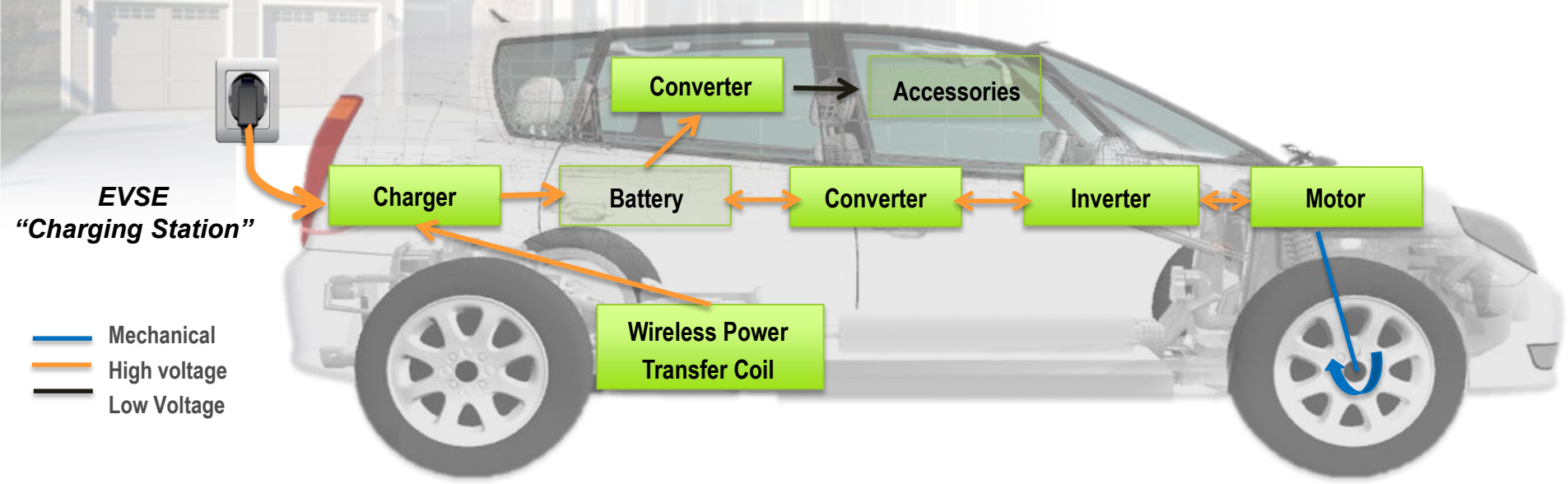


Innovation is necessary to accelerate vehicle electrification:

- ❑ **WBG power electronics to improve power density and reliability.**
- ❑ **Advanced magnets for electric traction drive motors.**

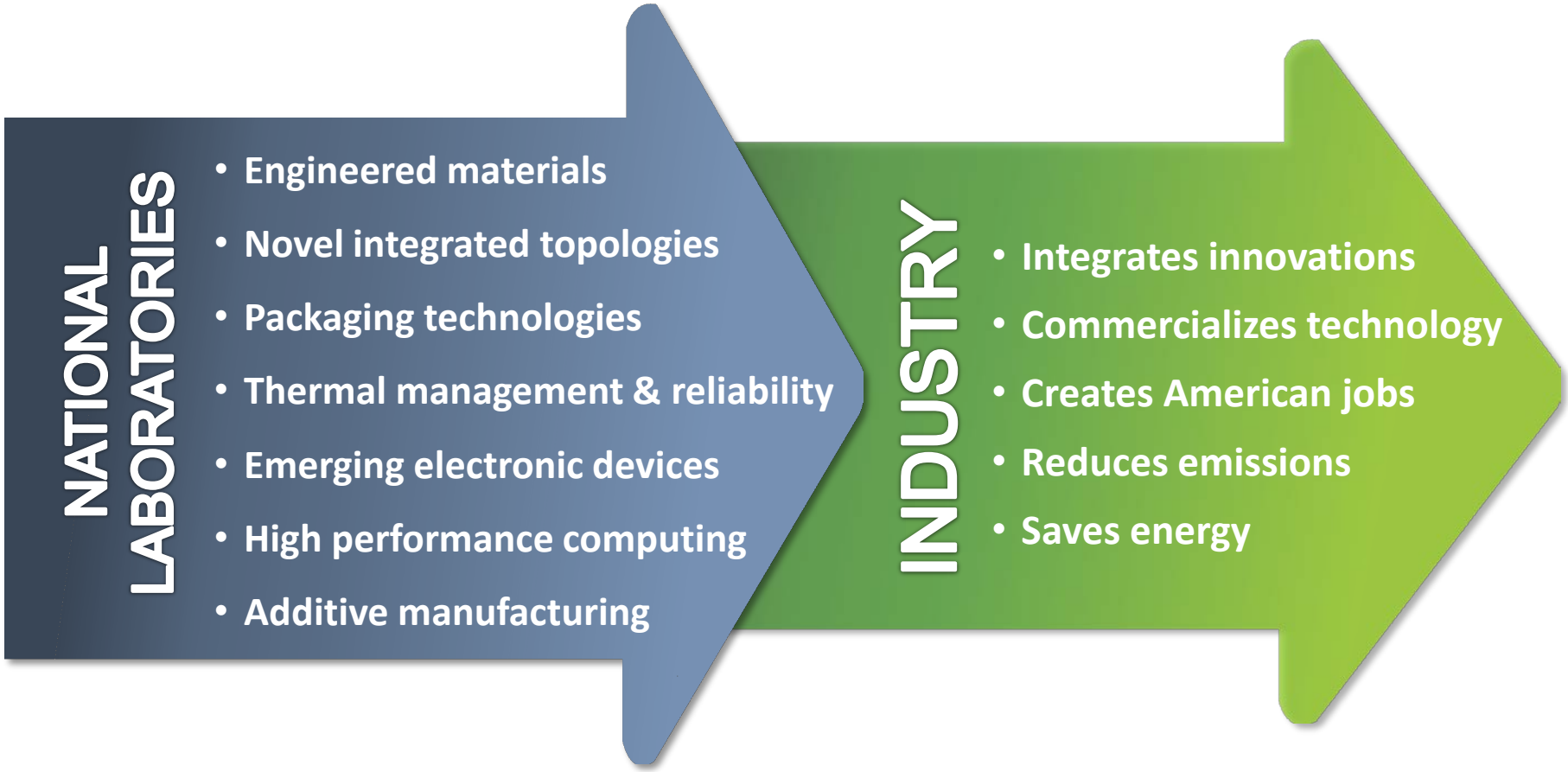
EDT Components

- **Electric motor** – converts electrical energy to mechanical power.
- **Inverter** – converts high voltage direct current to control power through the electric motor.
- **Charger** (with wireless option) – controls electrical energy to charge the battery.
- **Converter** – increases battery voltage for traction drive & decreases voltage for accessories.



Integration of components will reduce electric drive system cost and increase efficiency

EDT Research Partnerships Accelerate Innovations



EDT Research Leads to Innovations

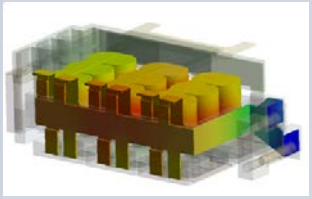
National Laboratory Expertise and Unique Capabilities

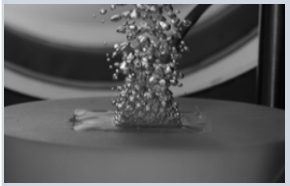
Oak Ridge National Laboratory (ORNL)

- Power electronics.
- Packaging.
- Wide Bandgaps (WBG).
- Electric motors.

National Renewable Energy Laboratory (NREL)

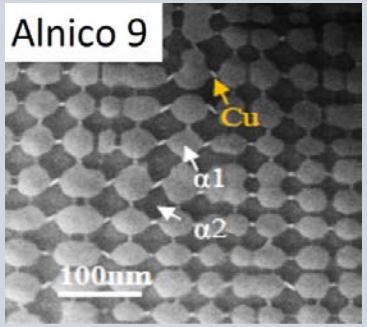
- Thermal management & reliability.

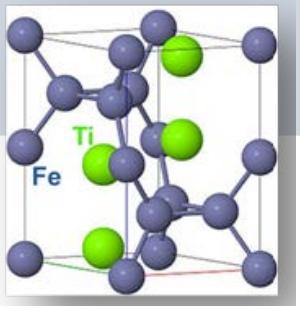




Ames Laboratory

- Magnetic materials.





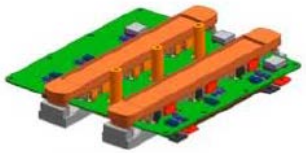
EDT R&D Highlights

Advanced inverter to be produced domestically

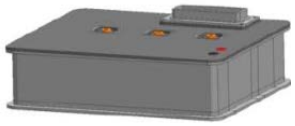
DOE-funded technology used in Volt traction drive inverter:

- ❑ 6% improvement in city cycle efficiency.
- ❑ 10% increase in fuel economy.

Discrete packaged Silicon unique to Delphi



Integrated PCB



Advanced Inverter

2016 Chevy Volt

Advanced manufacturing of traction drive inverters

First-of-its-kind, printed, all-silicon carbide traction drive inverter:

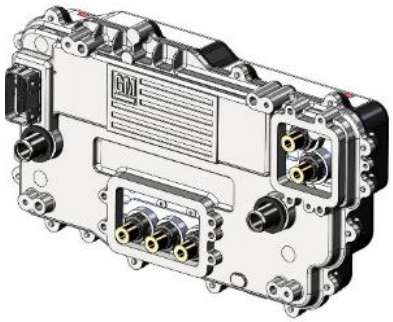
- ❑ 20kW power rating.
- ❑ ~ 50% printed parts.
- ❑ 98.7% rated efficiency.

Higher-power designs with increased integration.

EDT R&D Highlights

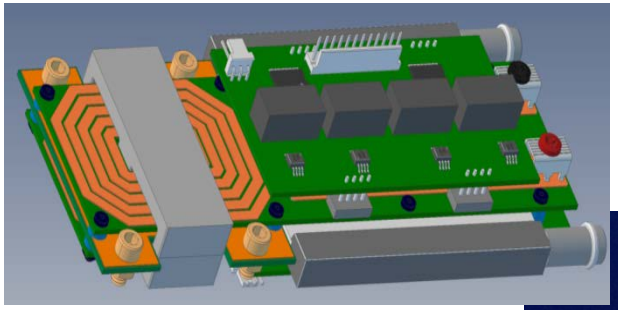
Next Generation Inverter

- When scaled to its highest power configuration, projected to meet 2020 cost target of $3.30/kW
- Meets 2020 traction inverter targets of 13.4 kW/L and 14.1 kW/kg.
- Highly consolidated design uses vertically integrated manufacturing processes.

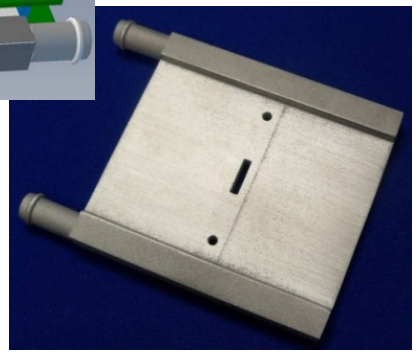


GENERAL MOTORS

6.6 kW GaN converter innovations reduce cost, weight, & volume by 50%



GaN Converter



3D printed cold plate

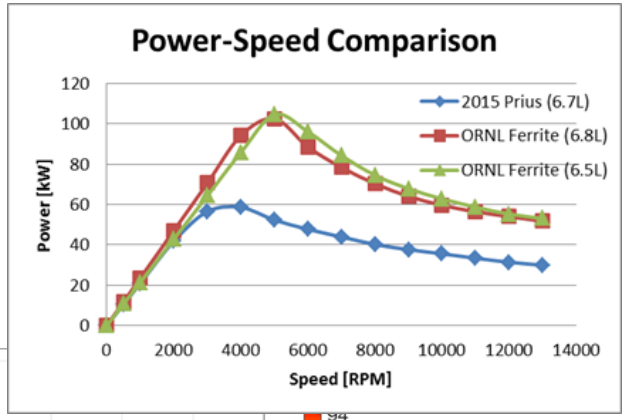
Technology innovations apply to converters and chargers:

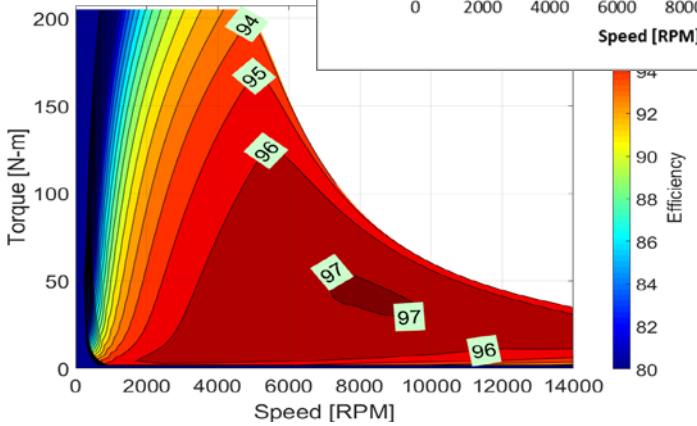
- High efficiency (>96%).
- 3D printed aluminum cold plate.
- 3D printed nano-composite magnetic cores.
- Parasitic inductance minimized.

EDT R&D Highlights

Non Rare-Earth Motor meets targets

- ❑ Low-cost ferrite PM motor designs.
- ❑ Same volume as the 2015 Prius motor with higher simulated peak power.
- ❑ Comparable efficiency throughout the torque-speed range.



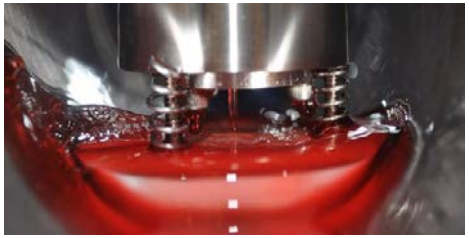


Thermal & Reliability data accelerates adoption of advanced technologies

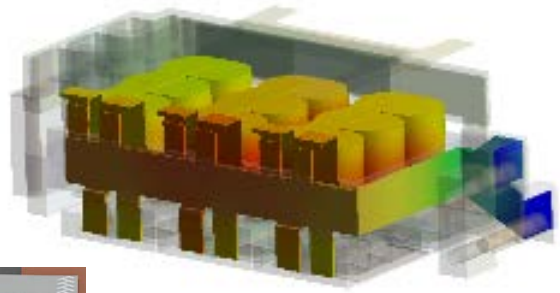
Technology innovations are evaluated for extreme automotive conditions:

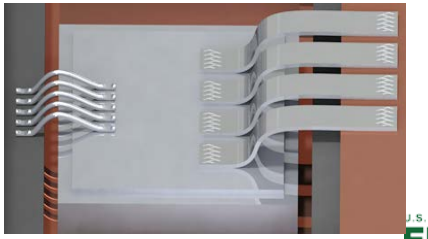
- ❑ WBG devices and supporting components.
- ❑ Ribbon interconnects.
- ❑ Motors.

Oil Cooling



WBG Inverter Thermal Map





Ribbon interconnects

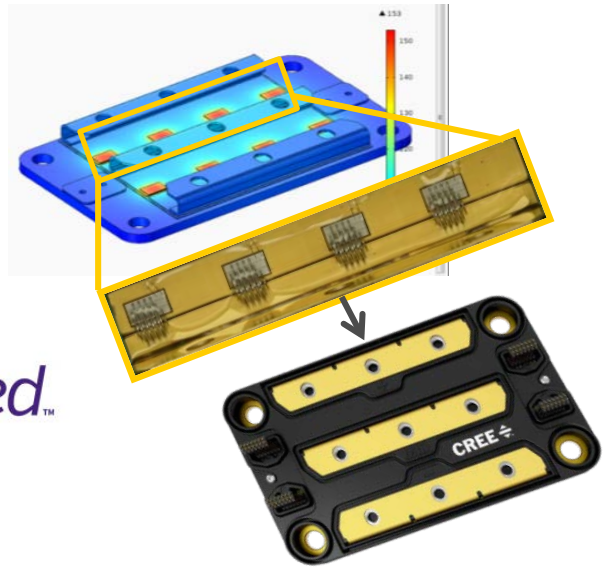
EDT R&D Highlights

88 kW Inverter with SiC Technology for EVs

Cree/Wolfspeed 900V SiC MOSFET:

- ❑ Reduces switching and conduction losses compared to IGBTs.
- ❑ Enables high frequency, power density, and efficiency and lower component count.

Inverter modeling demonstrated 67% loss reduction using the 900V SiC MOSFET.



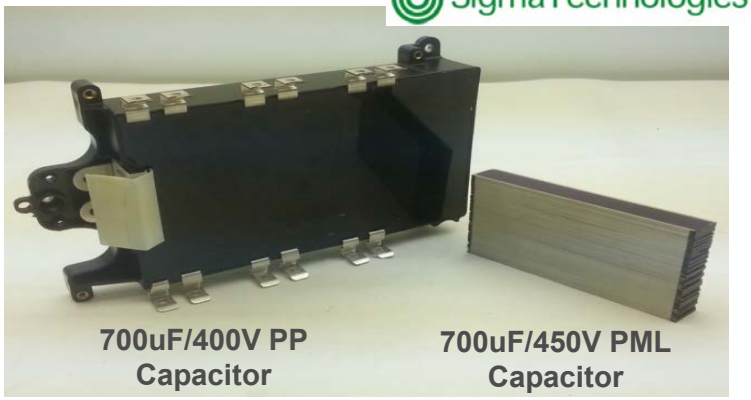
Wolfspeed™
A CREE COMPANY

High-Temperature dc-Bus Capacitor

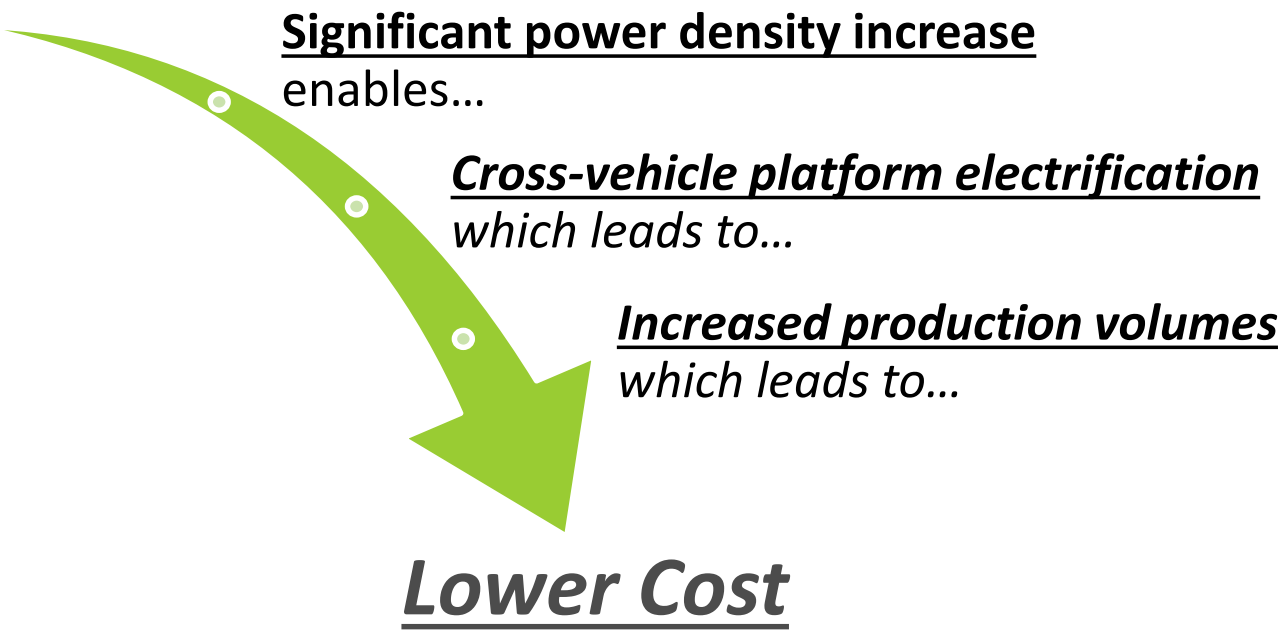
Sigma Technologies solid state Polymer-Multi-Layer (PML) capacitor:

- ❑ 3x improvement in energy density over state-of-the-art polypropylene capacitors.
- ❑ Cost projected to be below $30 per capacitor target.
- ❑ Testing validates performance for automotive requirements.

SigmaTechnologies



EDT - Looking Forward



- ❑ **Optimize power electronic designs to take full advantage of WBG capabilities.**
- ❑ **Reduce or eliminate rare earth magnets in electric motors.**
- ❑ **Integrate synergistic components.**

EDT Recent Patents

Patents Filed:

- I.E. Anderson, E.M.H. White, M.J. Kramer, A.G. Kassen, K.W. Dennis, “Solid State Grain Alignment of Heat Treatable Permanent Magnets in Near-Final Shape”, US provisional patent application (ISURF # 04487), March 31, 2016.
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- Moreno, G., Bennion, K., King, C., and Narumanchi, S., 2015, “Two-phase heat exchanger for cooling electrical components,” Non-Provisional Application No. 14/926,594 filed October 29, 2015 with the United States Patent and Trademark Office.
- Z. Liang, “Integrated Packaging of Multiple Double Sided Cooling Planar Bond Power Modules,” provisional patent application 62/167,371 filed for ID-3211, May 28, 2015.
- G.-J. Su, “Electric Vehicle Recharging and or Supplying Electrical Power,” DOE-S No.: S-124,506, Application #14/043,557, US Patent application published April 10, 2014.
- B. Ma, M. Narayanan, U. Balachandran, S. Chao, S. Liu, “Method for Fabrication of Crack-free Ceramic Dielectric Films”, US Patent Application 2014/0120736 A1, published on May 1, 2014.
- M. R. Fairchild, R. S. Taylor, C. W. Berlin, C. W. Wong, B. Ma, U. Balachandran, “PLZT Capacitor on Glass Substrate”, US Patent Application filed on October 22, 2013.
- M. Chinthavali, “Gas Cooled Traction Drive Inverter,” App. No: 14/016,327, DOE-S No. S-124,056, September 3, 2013.
- T. Burress and C. Ayers, “Reluctance Motor,” App. No.: 13/944,731, DOE-S No: S-124,185; July 17, 2013.
- M. Narayanan, B. Ma, U. Balachandran, S. E. Dorris, “Method for Producing Thin Film Electrodes”, US Patent Application 2013/0071670 A1, published March 31, 2013.

Patents Issued:

- M. Chinthavali, “Gas Cooled Traction Drive Inverter,” US Patent No. 9,320,179 B2, April 19, 2016.
- Z. Liang, P. Ning, F. Wang, and L. Marlino, “Power Module Packaging with Double Sided Planar Interconnection and Heat Exchangers,” US Patent No. 9,041,183, May 25, 2015.
- D. Bharathan, K. Bennion, K. Kelly, S. Narumanchi, “Fluid-Cooled Heat Sink With Improved Fin Areas and Efficiencies for Use in Cooling Various Devices,” US Patent No. 9,010,405 B1, issued on April 21, 2015.
- A. Wereszczak, “Sintered Silver Joints via Controlled Topography of Electronic Packaging Subcomponents,” US Patent No. 8,822,036 B1, issued on September 2, 2014.
- K. Bennion, M. Thornton, “Parallel Integrated Thermal Management,” US Patent No. 8,806,882 B2, issued on August 19, 2014.
- B. Ma, U. Balachandran, S. Chao, S. Liu, and M. Narayanan, “Method for Fabrication of Crack-free Ceramic Dielectric Films”, US Patent No. 8,647,737 B2, issued on February 11, 2014.
- K. Bennion and J. Lustbader, “Integrated Three-Dimensional Module Heat Exchanger for Power Electronics Cooling,” Patent No. US 8,541,875 B2, September 24, 2013.
- G-J. Su, “Electrical Motor/Generator Drive Apparatus and Method,” US Patent No. 8,373, 372; DOE-S No. S-115,264, February 12, 2013.
- Z. Liang et al., “Power Module Packaging with Double Sided Planar Interconnection and Heat Exchangers” Patent No. US 2013/0020694 A1, published January 24, 2013.

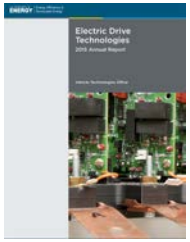
EDT Recent Inventions and Disclosures

Records of Invention/Disclosures:

- G. Moreno, K. Bennion, R. Farrington, “Jet impingement-Two-Phase Hybrid Thermal Management System for Hydrogen Pre-Cooling”, Record of Invention (ROI)-16-44, February 11, 2016.
- A. A. Wereszczak, Z. Liang, and T. A. Burress, “Enabling materials for high-temperature power electronics,” presented at the 2015 VTO AMR, Arlington, Virginia, June 10, 2015.
- A. A. Wereszczak, and W. Carty, “Drying Method for Sinterable Paste Used for Bonded Joints,” Invention Disclosure Number 201503507, DOE S-138,139, April 3, 2015.
- A. A. Wereszczak, S. B. Waters, and W. Carty, “Transfer Method for Printed Sinterable Paste Having Nonaqueous Solvent,” Invention Disclosure Number 201503508, DOE S-138,140, April 4, 2015.
- G. Moreno, K. Bennion, and S. Narumanchi, “Two-Phase System for Cooling a Vehicle’s Electric Motor and Power Electronics ,” ROI-14-67, May 30, 2014.
- B. Ma, U. Balachandran, S. E. Dorris, T. H. Lee, “Method For Making Wound Or Stacked Ceramic Films Capacitors With Enhanced Breakdown Strength,” Record of Invention ANL-IN-14-038, reported on April 3, 2014.
- K. Bennion, J. Lustbader, and R. Farrington, “Multiple Mode Cooling System for Power Electronics,” ROI-14-42, February, 2014.
- D. DeVoto and C. King, “Liquid thermal interface material for electronic component cooling and attachment,” ROI-14-21, December, 2013.
- A. Wereszczak, D. DeVoto, and P. Paret, “Perimetric Structure for Improved Reliability in Electronic Device Interconnection,” Invention Disclosure DOE-S No. S-124,788, October 2013.
- C. Ayers and J. M. Miller, “Hybrid Transflux Motor utilizing Variable Flux Intensifying and Weakening Operation,” Invention Disclosure IP-1250, September 10, 2013.
- B. Radhakrishnan and J. M. Miller, “Additively Manufactured Fe-6.5 Si wt. % Si steel Cores for Motor Applications,” Invention Disclosure IP1247, September 9, 2013.
- M. Chinthavali, “Novel Power Module Packaging Concept with Ceramics,” DOE-S No.: S-124,595, Disclosure No.: 201303015, February 13, 2013.
- G. Moreno, C. King, K. Bennion, S. Narumanchi, “Two-Phase Heat Exchanger for Power Electronics Cooling,” Record of Invention-13-00036, February, 2013.
- K. Bennion, J. Cousineau, and J. Lustbader, “Thermal Short-Circuit for Enhanced Power Electronics Cooling,” ROI-14-10, November, 2013.
- D. DeVoto, P. Paret, and A. Wereszczak, “Perimetric Structure for Improved Reliability in Electronic Device Interconnection,” ROI-14-20, November, 2013.

Information Sources

- **FY 2015 Advanced Power Electronics and Electric Motors Annual Progress Report:**
  - http://energy.gov/eere/vehicles/downloads/vehicle-technologies-office-2015-electric-drive-technologies-annual-rd



- **Electrical and Electronics Technical Team Roadmap:**
  - http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_june2013.pdf

- **EV Everywhere Blueprint:**
  - http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_blueprint.pdf

- **Vehicle Technologies Multi-year Program Plan 2011-2015:**
  - http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

- **2015 U.S. DRIVE Highlights of Technical Accomplishments Report:**
  - http://www.uscar.org/commands/files_download.php?files_id=424

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http://energy.gov/eere/vehicles/vehicle-technologies-office-electric-drive-systems

Backup Slides

EDT research projects at ORNL, NREL, and Ames

- **Drivetrain Benchmarking** – 2014 Honda Accord and 2016 BMW i3

- **Inverter** – 30 kW inverter utilizing a 1,200 V trench WBG power module
- **Converter/Charger** – 6.6 kW GaN converter with 3D printed cold plate
- **Control** – WBG gate driver with sophisticated control algorithms
- **Power Module**– air-cooled, high efficiency, SiC module
- **Bonded Interfaces** – reliability evaluated at 200°C
- **Heat Removal** – advanced cooling technologies and thermal modeling

- **Motor** – supercomputer optimization of non-rare earth motor designs
- **Motor Magnets** – enhanced alnico magnets
- **Motor Heat Removal**– data collection and analysis